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EXHAUST PRESSURE AND DENSITY OF VARIOUS PULSED MPD-ARC THRUSTER SYSTEMS

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Abstract

Exhaust flow in a new, 155 cm i.d., vacuum facility is compared with earlier measurements in a small (15.2 cm i.d.) duct. Reductions in post-transient impact pressure are about 5:1 in the larger facility. Corresponding reduced electron number densities ($\approx 2 \times 10^{13}$ cm^{-3}) are noted. A new, 125 microsecond, pulse forming network power source produced no major differences in impact pressure compared to the crowbarred condenser bank used earlier. Comparing a puff gas feed of the arc chamber with a new 10 millisecond steady gas feed also shows no major difference in impact pressure for 125 microsecond powering.

Introduction

The experimental data available on pulsed, megawatt MPD-Arc thrusters is difficult to correlate because each experiment has a different set of test parameters. Besides the usual engine geometry and propellant type variations from experiment to experiment there are other major differences. This paper compares experimental results from two different vacuum systems, power supplies, and propellant feed systems. Changes in the pulsed MPD-Arc thruster experiment at Lewis Research Center have provided the opportunity to make these comparisons.

Apparatus

Vacuum Facility

The initial experiments[1-4] employed a glass pipe exhaust flow duct, 15.2 cm i.d., 3 m long which was pumped by a 25.4 cm diameter diffusion pump system. The experiment was recently moved to a much larger vacuum facility shown in Figure 1. The vacuum tank is 5.3 m long by 1.55 m in diameter and is pumped by 4 diffusion pumps, each 0.9 m in diameter. The thruster is mounted on an insulating flange on an electrically floating, insulated spoolpiece, 0.9 m in diameter by 0.9 m long. Both the old vacuum system and the new facility were pumped to the low 10^{-6} torr pressure range prior to each thruster pulse. The much greater throughput of the new vacuum facility allows millisecond thruster operation with large propellant flows (grams per second) without increasing the transient tank pressure above 10^{-3} torr. The larger size of the new vacuum facility allows testing of the exhaust with much less wall interference.

Thruster

The thruster used in these experiments is the type described in refs. 1-4 for the self-field case. The arc chamber and valve assemblies are shown in cross section view in Figure 2. In Figure 2a the puff propellant valve of refs. 1-4 is shown in place. In Figure 2b the newly developed pulsed solenoid valve system is shown. The anode for all the experiments was made of copper, 4.12 cm inside diameter. The cathode was a 1 cm wide, 1 mm thick, tungsten ribbon (2 cm long) and was not heated prior to each pulse. The arc chamber geometry was maintained for all the experiments of this paper.

Propellant Systems

The experiments of refs. 1-4 employed an electromagnetic hammer actuated high-speed puff propellant valve system. The thruster was operated in the new vacuum facility with this type of propellant system for comparison with earlier work. This propellant system introduces a 90 microsecond duration puff of gas into the arc chamber. After a 650 microsecond settling time, the transient flow rate through the anode orifice has reached maximum value and the arc is electrically initiated. The arc is powered for a few hundred microseconds as the propellant in the arc chamber bleeds out of the anode orifice. Thus the mass flow rate is decaying with time as the arc is powered. The puff propellant system was employed in the earlier phase of the thruster program where the vacuum facility was small and had low throughput capability.

The thruster was also operated in the new vacuum facility with a newly developed pulsed solenoid valve propellant system. A commercially available miniature solenoid valve was modified to allow maximum flow rate. The valve was fed from a regulated high pressure reservoir. Instead of the usual 115 VAC, 60 Hertz, solenoid excitation, the solenoid was driven with a specially shaped voltage pulse. This pulse was generated by a gated reed relay system that applied a 350 volt spike, decaying in one millisecond to 100 volts. The latter portion of this applied voltage lasts for 10 milliseconds. The valve is "full open" in 2 milliseconds and steady flow is established through the arc chamber in 3.5 milliseconds. At this time the arc is ignited. Although the arc is powered for only a few hundred microseconds, the exciting electrical pulse for the valve lasts for 10 milliseconds. Thereafter a spring internal to the valve closes the valve after 40 milliseconds. The valve seals and operates properly up to 200 psig reservoir pressure. This allows a maximum flow rate of 1.5 gm/sec N_2.

Power Supplies

The experiments of references 1-4 were powered by a crowbarred capacitor bank[5] that was crowbarred at peak current to provide a monotonically decaying arc current for a few hundred microseconds. The crowbarred capacitor bank was also used to power the thruster operating in the new vacuum facility.

Another type of power supply was also used to power the thruster in the new vacuum facility. This is a newly developed pulse forming network (PFN) capacitor bank[6] that provides a square wave powering current for the arc. The PFN-capacitor bank provides up to 20 kiloamperes current for 125 microseconds and is shown with its solid state switching in Figure 3.

Impact Pressure Probe

A piezoelectric pressure probe, associated emitter follower amplifier and filter was used to measure impact pressure. It was initially described in refs. 7 and 8. The probe-amplifier system has an overall sensitivity of 40 volts per atmosphere. The filter is used to remove unwanted piezo crystal ringing from the measurement signal. The filter is set for a cut-off frequency of 50 kilohertz. The probe face has been mounted 30 cm downstream from the anode of the thruster and can be moved to various radial locations.

Number Density Measurement

The electron number density of the exhaust was measured using 90° Thomson scattering of the beam from a Q-spoiled ruby laser light pulse as described earlier in ref. 2. For this experiment, the laser power was increased, using an auxiliary optical amplifier, and the scattered light optics were improved significantly so as to allow almost an order of magnitude increase in sensitivity over earlier work. This allowed for measurements in the low 10^{12} cm^{-3} range.

Results and Discussion

In all cases described in this section the thruster geometry, cathode style, and propellant, nitrogen, were kept the same. No auxiliary magnetic field was used.

Vacuum Facility Effects

The impact pressure traces[1-4] described earlier for the self-field case in the 15.2 cm i.d. vacuum duct are shown in Figure 4a. By way of comparison, Figure 4b shows the impact pressure traces for the same condition but for the new 1.55 m i.d. vacuum facility. The same puff propellant system and crowbarred bank power supply (20 kA peak current case) were used in both facilities. The impact pressure after the starting transient is about 50 percent lower than for the smaller duct and is radially flat over the 2, 4, and 6 cm radial positions that were surveyed. In 100 microseconds that pressure is 20 percent of the pressure shown in Figure 4a for the equivalent time. The measured pressure traces are small and difficult to measure after the 300 microsecond time period. There is a thermally caused droop in the pressure record. This must be corrected for the pressure beyond the 150 microsecond time period and the data become uncertain and error laden because of this fact. At 150-200 microseconds time, well past starting transients, the impact pressure is a factor of five lower in the new and larger vacuum facility. This lower value of the pressure is spread over a much larger cross section of the exhaust profile. It was not possible to survey radially beyond 6 cm because of low signal sizes and large droop corrections. Thus it was not possible to estimate the thrust as was done in ref. 4 for the smaller duct.

The electron number density was measured in the new vacuum facility at the Z = 30 cm station. The thruster was powered by the PFN bank. The pulsed solenoid valve was used. The data obtained are shown in Table 1 as well as the data obtained earlier in the smaller duct[1]. The data of ref. 1 were for a larger mass flow rate. This would, at most, account for a factor of two difference in exhaust density, whereas one magnitude difference is noted on centerline. These are typical data for the time period in the exhaust cycle that is just past the initial starting transient. Just as in the impact pressure measurements case, the electron number density is between a factor of two to a factor of five lower in the large vacuum facility than in the smaller duct.

Power Supply Effects

Impact pressures measured at 30 cm downstream from the anode face in the new vacuum facility when the thruster is powered by the PFN-capacitor bank show much the same pressure trace shapes and amplitudes as was described in the previous section (Fig. 4b) where the thruster was powered by the crowbarred capacitor bank and exhausted into the new vacuum facility. That is, given the same vacuum facility, using the same self-field thruster, with the same <u>puff</u> propellant valve system, the type of powering for a 20 k A current case (crowbarred or PFN banks) does not change the impact pressure trace except in minute details that cannot be detected accurately with the present probe sensitivity. The PFN powering duration is 125 microseconds whereas the crowbarred capacitor bank decays almost linearly from peak current to zero in 500-800 microseconds. So for the first 125 microseconds, either power supply has a nearly flat (within 20 percent) current drive for the arc. Therefore it can be expected that the exhaust pressure ought to be about the same for the same propellant system during that time. The mass flow is decaying all through the powering cycle (see ref. 3) and thus, after 125 microseconds the mismatched decaying mass flow rate and the decaying current is reflected in the decaying pressure traces of Figure 4b.

Propellant System Effects

Exhaust impact pressure is expected to be affected by the type of propellant injection. This section identifies differences noted for the two different propellant systems. The tests were conducted in the large vacuum facility with the PFN-capacitor bank providing the power.

The puff propellant feed system was used in earlier work[1-4] and was particularly adapted to short duration (50-100 microseconds) thruster operation into limited vacuum facilities. In limited vacuum facilities, the task is to inject the propellant

a. with minimum fill-up time delay (for the arc chamber volume) so as not to flood the vacuum facility, and

b. to shut down the propellant flow as early as possible after the thruster powering time so as not to fill the vacuum facility with unused propellant.

The puff propellant feed system accomplishes this best if the decreasing mass flow is tolerable. The sequence of events is to fill the arc chamber from a fast acting (90 microsecond operating time) puff gas valve, allow a 650 microsecond settling time, and then power the arc for a short time while the mass flow of nitrogen is decreasing from maximum, 2.5 gm/sec to 2.0 gm/sec, 100 microseconds later. This 25 percent decay in mass flow rate was not a problem in preliminary investigations where short duration powering cycles are employed. It would obviously be a poor choice where longer powering time is demanded, say a large fraction of a millisecond.

In larger vacuum facilities, longer arc chamber fill-up time delays can be tolerated (slower acting valves) before arc ignition. Also, the valve can stay "full open" longer, allowing for constant flow attainment through the thruster provided a constant current power supply is available for prolonged powering times. The fast shut down requirement is not as demanding in a large vacuum facility. Thus a fast acting solenoid valve can be applied to meet these reduced requirements. The sequence of events is to fill the arc chamber for 3.5 milliseconds. Then the arc is powered for as long as the supply can provide constant current (125 microseconds for the present PFN bank, although the valve system can accommodate 10 millisecond powering times). The mechanical return spring in the valve shuts down the valve after this time. A delay of almost 41 milliseconds occurs before the spring closes the valve.

Unfortunately, the pulsed solenoid valve cannot shut off completely at pressures above 200 psi. This limits the mass flow rate to 1.5 g/s N_2. The puff propellant valve provided 2.5 to 2.0 g/s N_2 at arc powering time. Thus the two systems cannot be compared directly but some general comments can be made:

1. The impact pressure traces show some droop at later times in the puff propellant system. The pulsed solenoid valve pressure records show no droop for the powering period.

2. Even the new vacuum system cannot keep up with the 1.5 g/s N_2 flow rate. The longer the flow rate persists prior to powering, the higher the vacuum system pressure will rise. The pulsed solenoid valve is open for 3.5 msec before the flow is steady. Using the laser scattering apparatus to measure the cold gas density at the $Z = 30$ cm station (and just prior to arc powering time) shows the cold gas pressure near the thruster to be from 0.2 - 0.5 mm Hg. At the opposite end of the tank, the pressure is in the micron range. There is a large cloud of cold gas near the thruster and this certainly affects the ability of the thruster to get to a stable running condition.

3. Propellant flow rate, powering time, and size of vacuum facility are interrelated. But increasing the propellant flow rate puts a heavy demand on increased vacuum facility size and throughput. Large flow rates mean much larger mass loads on the vacuum facility. The larger valves open slowly, and shut much more slowly. By way of comparison, the puff gas valve opens and closes in 90 μsec, and it takes 0.65 msec before steady flow is developed at the anode and the arc can be powered. On the other hand, the pulsed solenoid takes 0.5 msec to open, 3.5 msec to develop steady flow at the anode, and 41 msec to close. The pulsed solenoid valve system loads the vacuum facility by at least two more orders of magnitude of mass than the puff system. It does provide steady flow for at least 100 msec if needed, vacuum system size determining this practical time.

Summary

The megawatt MPD-Arc thruster exhaust was examined with an impact pressure probe, and electron number density was determined through a laser scattering system. The exhaust was measured in a new and larger vacuum facility and compared to earlier work in a smaller glass duct vacuum system. At times immediately after the initial blastwave the impact pressure and density in the larger vacuum facility is one-fifth that of the values reported earlier for the small facility.

For the same puff propellant system and the new vacuum facility, two modes of powering the arc were compared. Only minor differences in the exhaust are noted for the 16 kA operation of the arc powered by either a crowbarred capacitor bank or a pulse forming network (PFN) bank. This holds only for the 125 μsec powering time. Differences exist if powering times are longer. A crowbarred bank provides decaying current with time, whereas the PFN bank (extended in design to the proper time) will provide a constant current.

For the same PFN powering system, two propellant systems were compared in the new vacuum facility. One was an electromagnetic hammer-actuated fast gas valve (puff valve) and the other a specially powered pulsed solenoid valve. For 125 μsec powering times, the puff valve produced a flow that decayed from 2.5 to 2.0 g/s. For longer times, 0.5-10 msec, the pulsed solenoid valve provides constant flow but is slower to open and much slower to close after the powering time. This puts a heavy load on the vacuum facility and ultimately limits the powering time before the vacuum environment is spoiled to about 100 msec.

References

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Table 1 Typical Electron Number Density (Self-field, Z = 30 cm, measured just after transient spike has passed)

RADIUS, cm	NUMBER DENSITY cm^{-3}	
	NEW VACUUM FACILITY 1.5 g/s N_2 16 kA SQUARE WAVE	15 cm I.D. GLASS DUCT 2.5-2.0 g/s N_2 16 kA MEAN RAMP
0	1.0×10^{13}	1.0×10^{14}
2	1.8×10^{13}	0.8×10^{14}
4	0.6×10^{13}	1.0×10^{14}

E-7650

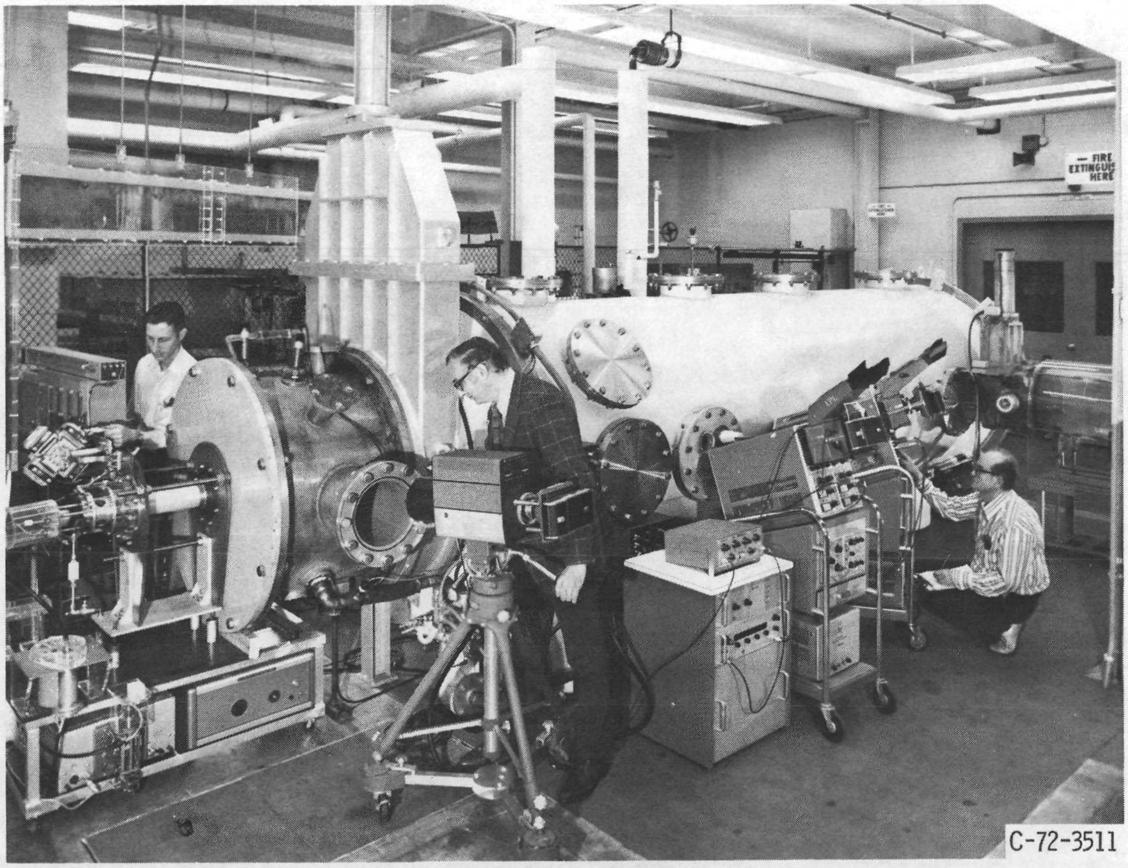
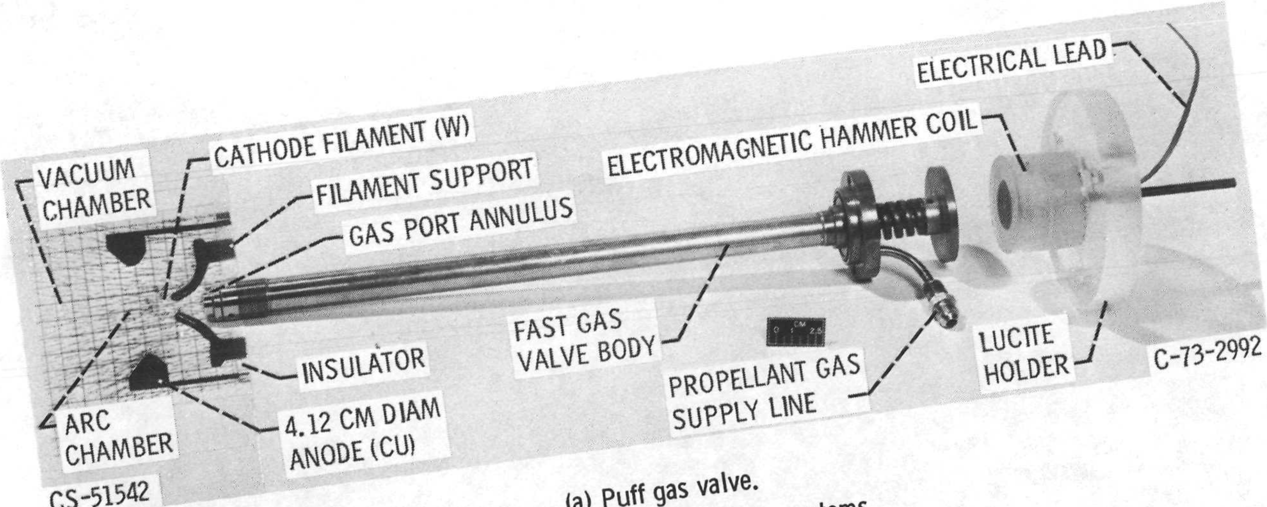


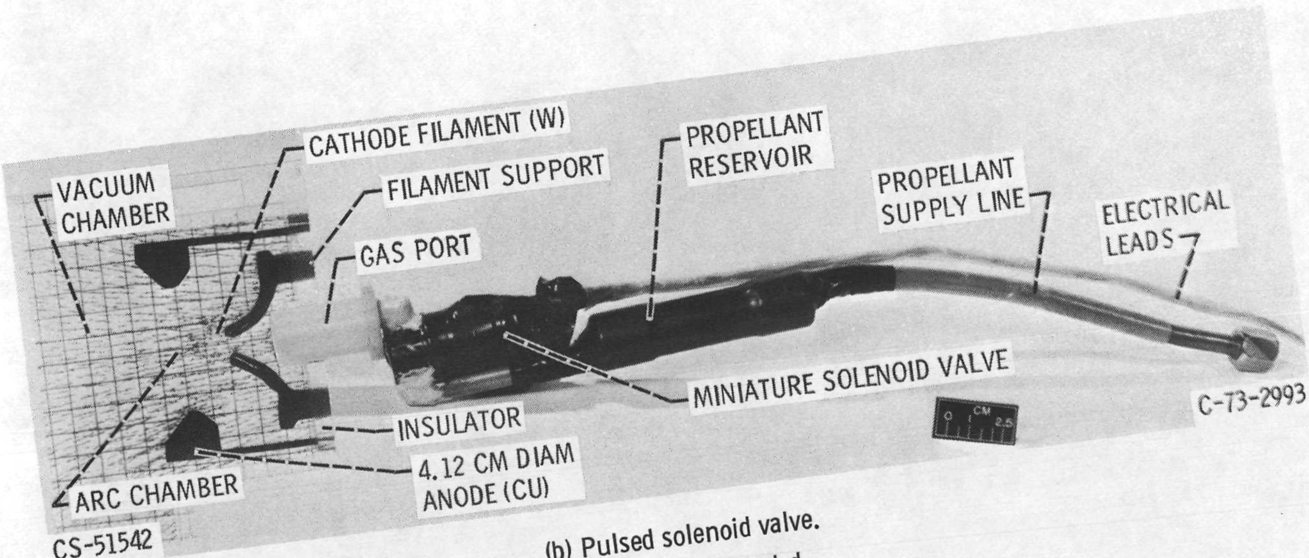
Figure 1. - New vacuum facility.



(a) Puff gas valve.

Figure 2. - Propellant valve systems.

E-7650



(b) Pulsed solenoid valve.

Figure 2. - Concluded.

E-7650

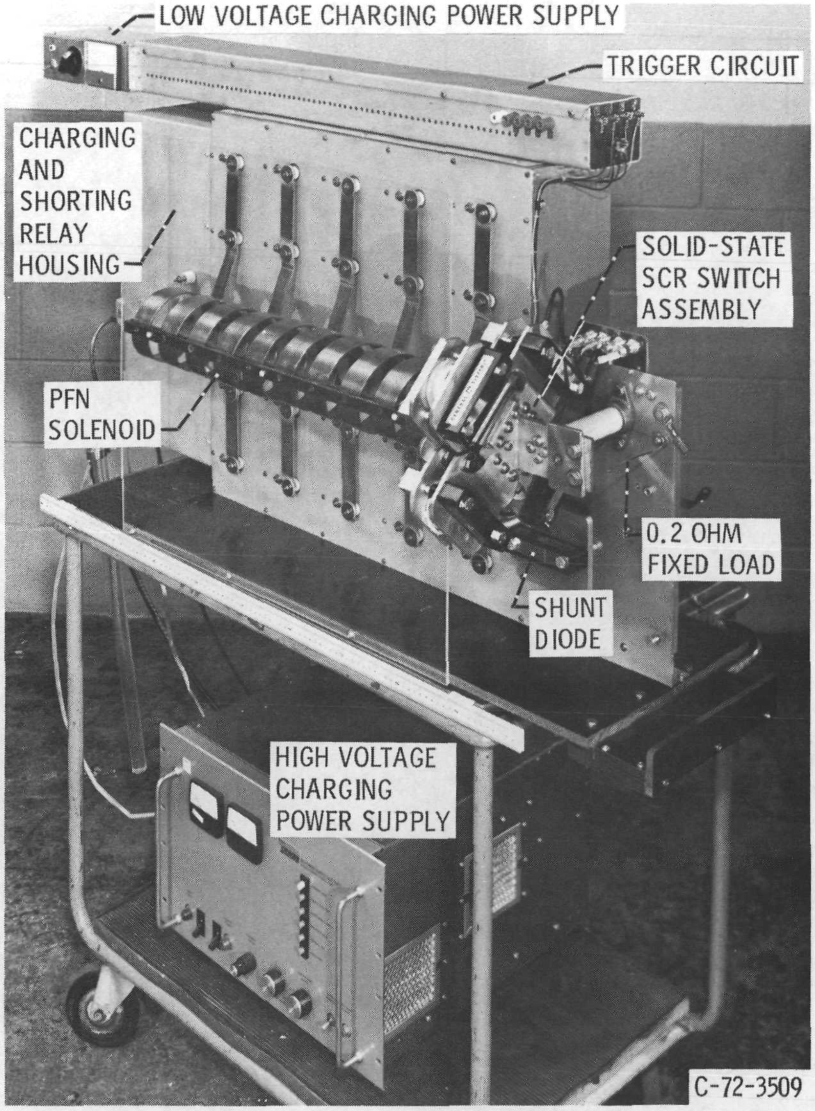
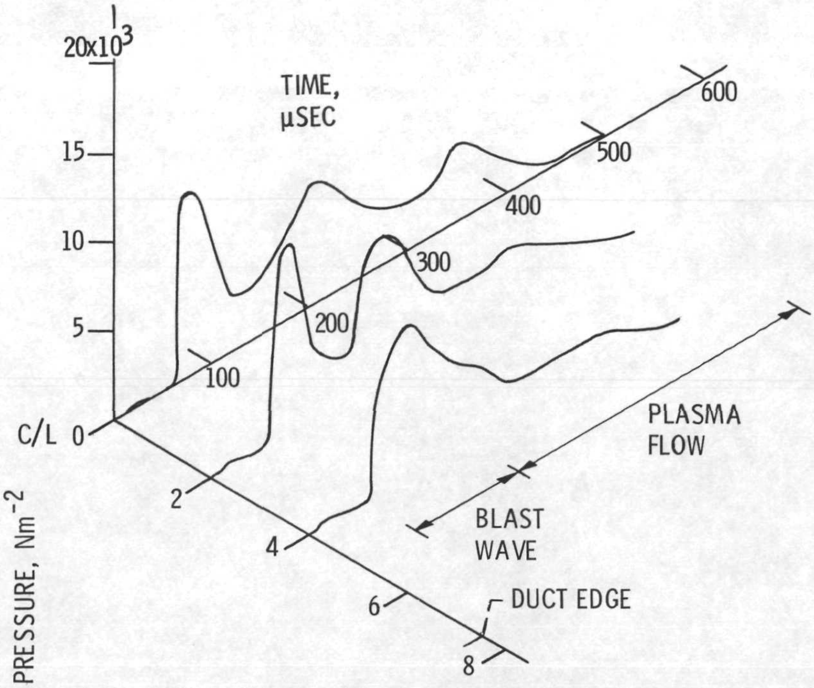
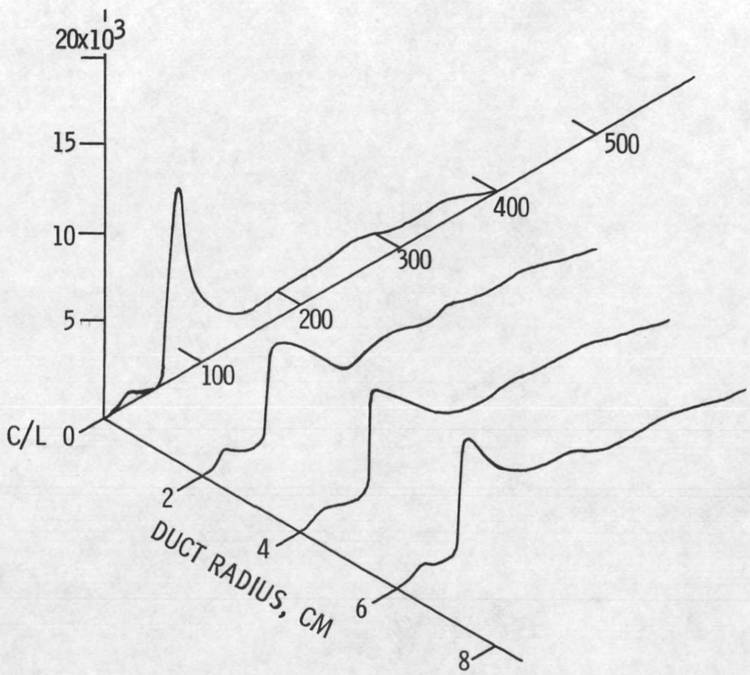


Figure 3. - Pulse forming network - capacitor bank.



(a) SELF-FIELD CASE, 15.2 CM DUCT (DATA OF REF. 3).



(b) SELF-FIELD CASE, 1.5 M NEW VACUUM FACILITY.

Figure 4. - Impact pressure profiles (20.0 kA peak current case).